WHICH CAPACITOR?

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INTRODUCTION

As our electronic circuitry progresses through its various stages of sophistication, the proper application of the individual circuit elements becomes progressively critical. From the breadboard (make something work) stage; through the pilot production (reduce size but make it work better), first-generation production (debugging), succeeding generation production (decrease sizes, increase reliability); to the ultimate goal of sub-miniature size coupled with an ultra-high reliability level, the selection of the components to be used to perform certain functions will be a determining factor that decides success or failure of the project.

This paper is an attempt to provide information that will assist parts application and design engineers in their job of selecting the proper capacitors for use in their circuitry. Particular emphasis is placed on the film dielectric type capacitors, but other types of dielectrics are compared and discussed briefly. Most application, environmental, and reliability discussion notes are applicable to all types of capacitors.

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WHAT IS A CAPACITOR?

Ask three people to define a capacitor and you will probably get three different answers — all of them somewhat correct — but usually not complete. Let us examine three typical answers to the question.

1. A capacitor is an electrical device capable of storing electrical energy for release at some predetermined rate at some predetermined time.

There is no question that this is a classical, correct, and generally accepted definition. But — it really doesn't tell us what the capacitor **is** — rather it describes what the capacitor **does.**

2. A capacitor is two metallic conductors isolated from each other by a suitable non-conducting dielectric material.

Now we have a definition that really tells us what makes a capacitor. But, by this definition, almost everywhere you turn — there's a capacitor of some sorts.

3. A capacitor is something that an electronic circuit won't work without.

Although this was given as a definition by a non-technical friend of mine, and the thought expressed is certainly appropos despite the shudders it may give any English instructor, it still remains a questionable statement rather than a definition.

If we combine the first two definitions, our resulting statement will provide a correct, descriptive, and workable answer to "what is a capacitor?"

"A capacitor is an electrical device, consisting of **two metallic conductors** isolated from each other by a suitable non-conducting **dielectric material,** that is capable of **storing electrical energy** for release at some **predetermined rate** at some **predetermined time."**

Now that we have defined a capacitor, let us next correlate this definition to a drawing of the capacitor and the associated circuitry that will allow the capacitor to perform fully to its definition.

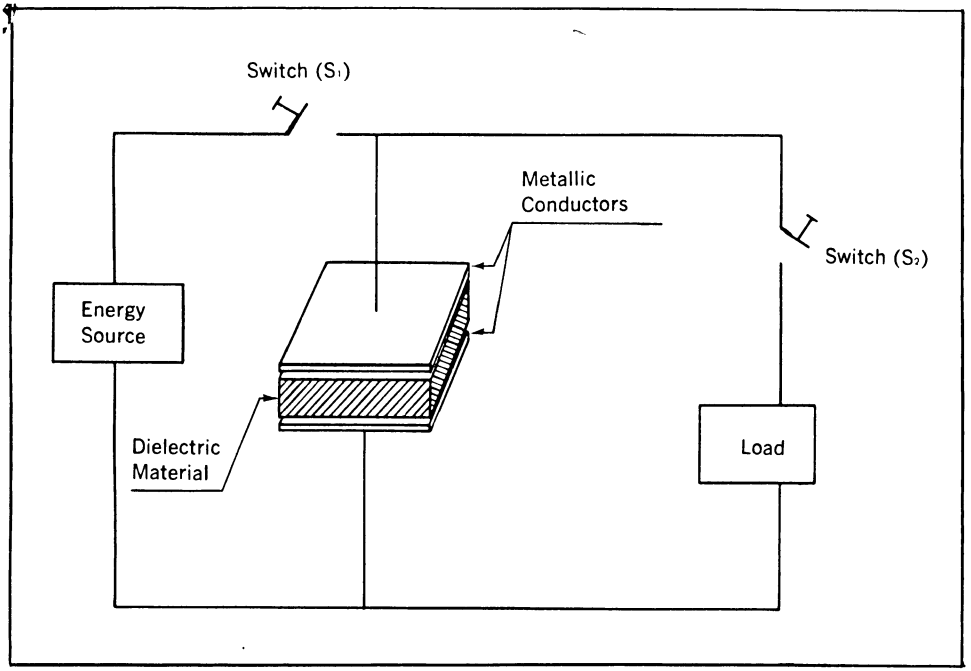


FIGURE 1

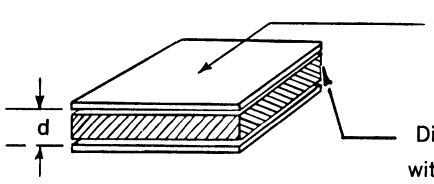
Figure 1 now shows us all of the factors contained in our definition. The "two metallic conductors", and the "dielectric material" are apparent. The addition of the plate connections, Switch S_1, and the energy source allows the capacitor to fulfill its function of "storing electrical energy". The plate connections, switch S_2, and the load, control the energy release factors of "predetermined rate" and "predetermined time".

HOW IS A CAPACITOR MEASURED?

Now that we know what a capacitor is and basically how it works, we must have some means of measuring its abilities or usefulness — and since its usefulness is that of "storing electrical energy" — its ability to store energy is the way we measure it. The term used to describe this ability is "capacitance".

Capacitance then is a measure of the quantity of electrical charge that can be held per unit of voltage differential between the metallic conductors (electrodes). The basic unit of capacity (capacitance) is the farad; however, since the farad is a very large quantity, microfarad (one millionth of a farad) and picofarad (one millionth of a microfarad) are generally used.

Now — how do we determine this capacitance figure? Figure 2 shows the basic formulas for calculating this capacitance and provides a very brief summary of how the formula was derived.



$$C = \frac{Q}{V} = \frac{\sqrt{\frac{KAf}{2\pi}}}{d\sqrt{\frac{8\pi f}{KA}}} = \frac{1}{d}\sqrt{\frac{K^2A^2}{16\pi^2}}$$

$$C = \frac{KA}{4\pi d} \text{ statfarads}$$

Q = charge in statcoulombs
V = potential in statvolts
K = dielectric constant
A = area in square centimeters
f = force between plates in dynes
d = distance between plates in centimeters

Converting to farads and inches we get:

$$C = \frac{KA}{4\pi d} \times (1/9 \times 10^{-11}) \times 2.54$$

$$C = \frac{.224KA \times 10^{-12}}{d} \text{ farads}$$

1 farad = 9×10^{11} statfarads
1 inch = 2.54 centimeters

FIGURE 2

We now see that our measuring factor capacitance (C) is controlled by the dielectric constant (K) of the material between the plates, the area (A) of the plates, and the distance (d) between the plates.

WHAT IS DIELECTRIC CONSTANT?

Inasmuch as both A and d in our formula for capacitance are geometrically determined figures, it appears that for any given set of A and d dimensions we can control the final value of capacitance by controlling the K (dielectric constant). This, in turn, tells us that different materials will give different values of capacitance for the same size unit. Now the question arises — what does "dielectric constant" mean, and how is it determined?

The dielectric constant of a material is a direct measure of its ability to store electrons when compared to air.

If we take a capacitor of given A and d dimensions and use just air as the dielectric material between the plates, we will measure a certain value of capacitance. Next, we substitute some other dielectric material for the air and again measure the capacitance. Now we find that we have, for example, twice as much capacitance. This means that our second dielectric material stored twice as many electrons as did air. Consequently, the dielectric constant of the second material is twice that of air.

Air (or to be precise — vacuum) has been arbitrarily assigned a dielectric constant value of 1.0. All other dielectric materials will store more electrons than air and therefore have dielectric constants greater than 1.0.

Figure 3 is a chart of various dielectric materials and their dielectric constants. The use of the approximate ($\approx$) sign rather than an equal sign is due to the fact that these dielectric constants will vary somewhat with purity, temperature, frequency, voltage, treatment during manufacture, and various other minor factors.

Dielectric Constants at +25°C

Dielectric Material	(K) Dielectric Constant
Vacuum	1.0
Air	1.0001
Teflon	$\approx$ 2.0
Polystyrene	$\approx$ 2.5
Polycarbonate	$\approx$ 2.7
Mylar	$\approx$ 3.0
Polyethylene	$\approx$ 3.3
Kraft paper	$\approx$ 2.0 to 6.0
Mica	$\approx$ 6.8
Aluminum Oxide	$\approx$ 7.0
Tantalum Oxide	$\approx$ 11.0
Ceramics	$\approx$ 35.0 to 6,000 +

$$C \propto \frac{KA}{d}$$

FIGURE 3

It would now appear that there is nothing really complicated about a capacitor — it seems very simple to build — just use the highest dielectric constant material available, press it as thin as possible, and we'll have our capacitor.

True! — Capacitors aren't really very complicated to build — but as soon as we apply these capacitors in certain circuits to do certain jobs, the complications begin. Suddenly, we find that only certain types of capacitors will work in some circuits, or that some types perform better than others. Why should this be so? In order to answer this question, let's examine some of the jobs that these capacitors are expected to do.

WHERE ARE CAPACITORS USED?

We have seen that the basic function of a capacitor is that of storing electrical energy. However, this basic function coupled with other circuit elements and/or other capacitor characteristics enable us to utilize the capacitor in many ways. Some of the most common uses are:

Blocking: Whenever direct current is applied to the capacitor, the capacitor effectively "blocks" this current and will not allow it to pass through. Therefore, whenever we wish to keep a DC signal from appearing across a portion of a circuit, we can use this "blocking" characteristic of the capacitor to accomplish this function.

Coupling (De-Coupling): Just as the capacitor will block out a DC signal, it will appear to pass an alternating current (AC) signal. The capacitor is really charging and discharging in opposite directions each half-cycle as the impressed AC voltage alternates in polarity. To the rest of the circuit this has the same effect as though the capacitor were allowing the passage of the AC signal. We use this characteristic of the capacitor to "couple" (or de-couple) an AC signal from one portion to another portion of the circuit.

By-Passing: This job is a good example of the combination of blocking and coupling functions. In this case, the capacitor is used to separate the DC and AC portions of a mixed signal current. Here, the capacitor is placed in parallel with another circuit element and serves the purpose of "by-passing" the AC portion of the mixed signal around the circuit element. We want the DC signal to appear on the circuit element — but not the AC signal. The DC portion of the signal sees a very high impedance path through the capacitor and therefore travels through the lower impedance path of the circuit element. The AC portion of the signal sees exactly the opposite than the DC portion and therefore, in effect, travels through the capacitor.

Frequency Discrimination: Closely related to the "by-passing" function is a characteristic of the capacitor whereby certain AC frequencies are allowed to pass more easily than others. In general, as the capacitance increases, more AC current will pass for any given AC frequency. Also, more AC current will pass as the AC frequency increases (up to the resonant frequency of the capacitor — the point of maximum current flow). By utilizing this characteristic of the capacitor, we can now distinguish between AC currents of different frequencies.

Timing: This function is really a control on the "speed of response" of the charging and discharging time for a capacitor and its associated circuitry. The rate at which charge flows in and out of the capacitor is directly controlled by the capacitance and resistance (R) of the circuit. Therefore, we control the "timing" by using various combinations of R and C. This combination of R and C is known as the "RC" or "time constant".

Transient Voltage Suppression: This characteristic of the capacitor is widely used to provide "voltage stabilization". Most unregulated circuits are subject to transient peaks of voltage surges which can cause malfunctions in the circuit. By utilizing capacitors, these transient peaks are absorbed or stored by the capacitor and a steady voltage signal is supplied to the circuit. This same principal is used to reduce AC ripple voltages in rectified power supplies.

Energy Storage: By using capacitors to store energy over a long period of time

and then discharging this total energy in a very short time, high currents can be made available to perform welding, photo-flash, heating, and other jobs.

Arc Suppression: "Make-Break" type circuits, whereby mechanical relays or similar devices are used to periodically interrupt a current flow, causes arcing at the contact points. This results in a "noise" signal that can interfere with nearby radio and television reception. The use of capacitor-resistor and/or inductor combinations will reduce or eliminate this interference and prolong the life of the contacts by absorbing the voltage pulse resulting from this current interruption.

Power Factor Correction: Part of the total power generated by, or supplied to, a circuit does not do useful work, but instead is used to energize certain components within the circuit. This % loss of power can be and is reduced by the use of capacitors to improve or "correct" the power factor of the circuit.

Most other applications such as voltage and frequency doubling, commutation, etc., are really special applications of one or more of the basic functions described above.

CAPACITOR CHARACTERISTICS — HOW DO THEY BEHAVE?

In our circuit applications, the capacitor can be and is subjected to various conditions of voltage and current ranging from a very simple DC application of a battery source, to extremely complex voltage and current wave-shapes resulting from AC generating equipment. Different types of capacitors will react differently to these conditions — and this factor can be very critical to the proper functioning of our circuit.

Capacitance Change with Temperature. Temperature variations have an effect on the capacitance of all types of capacitors. Some will react only slightly, others will react moderately, still other react most violently.

A major reason for this capacitance variation with temperature is directly traceable to the fact that the dielectric constant of the material changes with temperature.

Figure 4 compares the typical temperature coefficient curves of the commonly used plastic films.

It should be noted that the curves shown in Figure 4 are for non-impregnated units. That is, a dielectric liquid (or solid) has not been added in the construction of the unit to impregnate the film. Actually, a plastic film will not really impregnate, and the impregnant (or filler) serves to replace part of the air film. When this happens, the resultant dielectric constant will vary slightly, thus altering the temperature coefficient curve proportionately.

Figure 5 illustrates some average TC curves that are obtainable with impregnated kraft paper dielectrics. In this case, due to the high porosity of the paper, the impregnation is virtually a necessity and, depending on the impregnant, a variety of TC curves are obtainable.

Many other liquid and solid impregnating dielectrics are used in conjunction with paper. Then, to further complicate the curves, various additives are used to "stabilize" or change the normal curves. Size and performance become the critical factors affecting the choice of which impregnant is chosen.

Figure 6 compares typical TC curves of other type dielectrics.

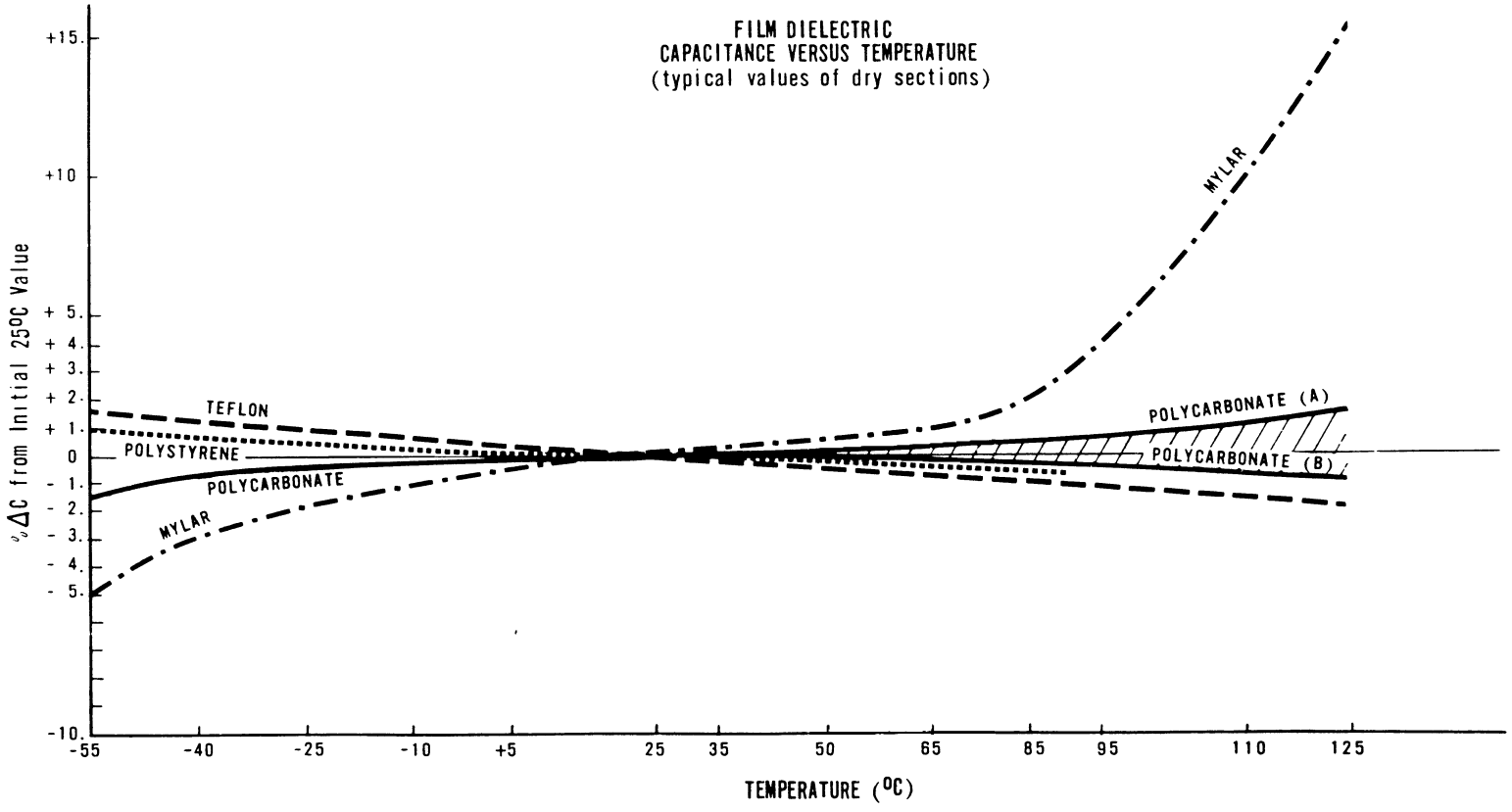

FILM DIELECTRIC
CAPACITANCE VERSUS TEMPERATURE
(typical values of dry sections)
+15.
+10
+ 5.
+ 4.
+ 3.
+ 2.
+ 1.
0
- 1.
- 2.
- 3.
- 4.
- 5.
-10.
% ΔC from Initial 25°C Value
TEFLON
POLYSTYRENE
POLYCARBONATE
MYLAR
MYLAR
POLYCARBONATE (A)
POLYCARBONATE (B)
-55
-40
-25
-10
+5
25
35
50
65
85
95
110
125
TEMPERATURE (°C)

FIGURE 4

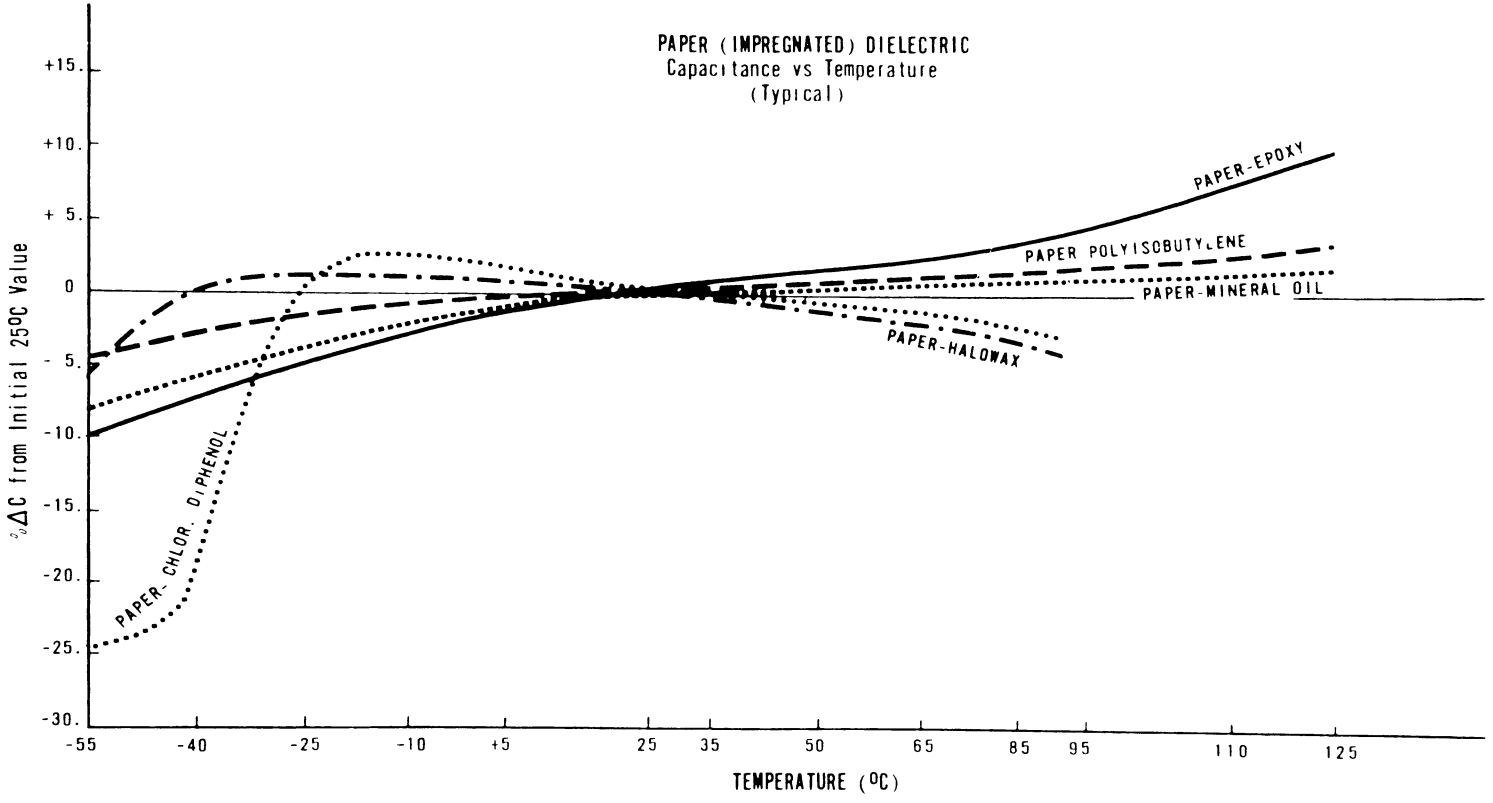

PAPER (IMPREGNATED) DIELECTRIC
Capacitance vs Temperature
(Typical)
+15.
+10.
+ 5.
0
- 5.
-10.
-15.
-20.
-25.
-30.
%ΔC from Initial 25°C Value
PAPER-EPOXY
PAPER POLYISOBUTYLENE
PAPER-MINERAL OIL
PAPER-HALOWAX
PAPER-CHLOR. DIPHENOL
-55
-40
-25
-10
+5
25
35
50
65
85
95
110
125
TEMPERATURE (°C)

FIGURE 5

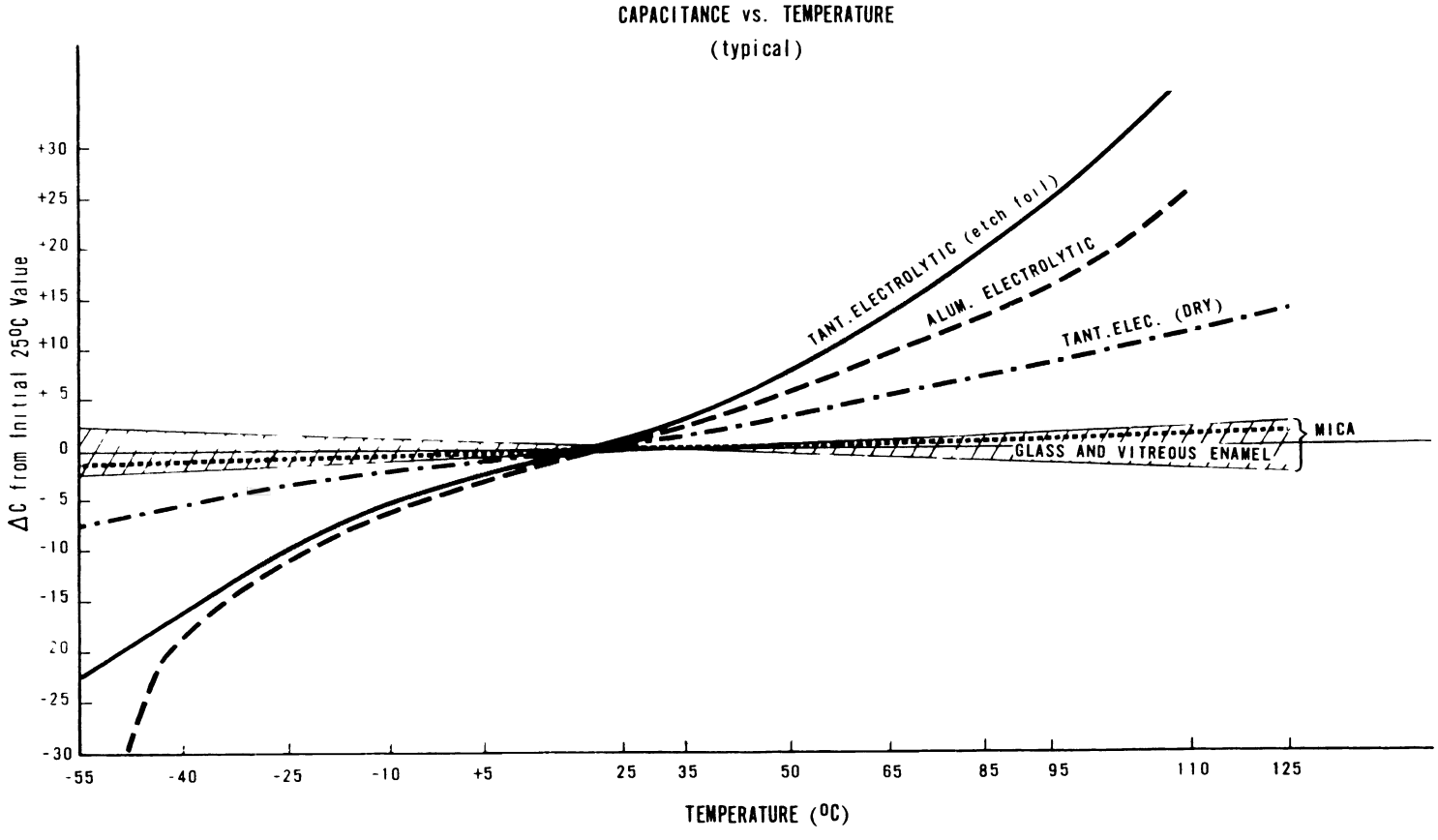

CAPACITANCE vs. TEMPERATURE
(typical)
ΔC from Initial 25°C Value
+30
+25
+20
+15
+10
+ 5
0
- 5
-10
-15
-20
-25
-30
TANT. ELECTROLYTIC (etch foil)
ALUM. ELECTROLYTIC
TANT. ELEC. (DRY)
MICA
GLASS AND VITREOUS ENAMEL
-55
-40
-25
-10
+5
25
35
50
65
85
95
110
125
TEMPERATURE (°C)

FIGURE 6

For the case of ceramic type capacitors, a plot of a "typical" capacitance vs. temperature curve is not feasible since these units can be made to exhibit almost any characteristics desired depending on the dielectric mixture used, processing, method of assembly, and stabilization techniques used following manufacture.

The capacitance change with temperature (temperature coefficient) characteristic is of critical importance in a good many circuits where the correct functioning of the circuit depends upon the capacitance value remaining within very tight tolerance limits over a prescribed temperature range. A prime example of this requirement is in the "timing circuit" designs in radar, computer, telemetering, and signal generation equipment. Incorrect values of capacitance can "jam" the device by altering the speed of response required, or supply incorrect data to a memory bank or servo-mechanism.

Power Factor Change With Temperature

In any electrical device, including capacitors, when we apply a certain amount of total energy (power) into the device, we get a lesser amount of energy out of it. The difference between the amounts in and out is "lost" or used within the device and is referred to as the "power loss". If we now divide this "power loss" by the input power, the resulting ratio figure gives us a measure of the "inefficiency" of the capacitor. Converting to a % figure by multiplying by 100, we arrive at the "% power factor" value. However, we generally speak of the "% dissipation factor" for most capacitors, and then to further complicate the picture, many references are made about the "Q" of a capacitor. Before proceeding to a look at the dissipation factor vs. temperature characteristics of our capacitors, let's determine and examine the relationships between these terms of "power factor", "dissipation factor", and "Q". (Figure 7.)

A word of caution is appropriate here in relation to these PF, DF, and Q concepts. You will note that all of the formulas invovle the f (frequency) term, so it becomes quite obvious that each of these concepts are highly dependent upon the frequency. For instance:

$$DF = \frac{R}{X_C} = \omega CR = 2\pi fCR$$

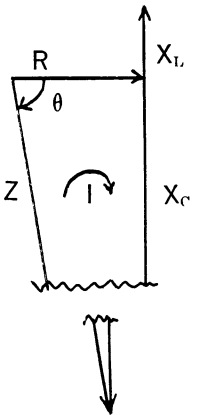
At first glance, an immediate conclusion presents itself that the DF is directly and linearly proportional to frequency (f) and therefore a simple proportion formula exists. What is not recognized implicitly is the fact that both C (capacitance) and R (resistance) are also effected by frequency and therefore the DF is a complex function of frequency. This aspect will be covered in more detail later in this paper.

Figure 8 shows the dissipation factor variation with temperature for the film dielectrics.

As is the case with the capacitance change with temperature, the inclusion of solid or liquid "filler" with the film dielectric will also alter the "DF vs. temperature" curves slightly.

Figure 9 shows some average DF vs. Temperature curves for the paper (impregnated) dielectrics.

Again we are faced with the problem of trying to depict typical curves for paper impregnated capacitors that can be altered (some quite drastically) by the addition of special additives and special processing techniques. In general, however, the addition of additives is a somewhat critical operation inasmuch as you



$I = I_Z = I_R = I_C$

Where:

R = effective series resistance in ohms

$X_L = 2\pi fL = \omega L$ = inductive reactance in ohms

$X_C = \frac{1}{2\pi fC} = \frac{1}{\omega C}$ = capacitive reactance in ohms

$Z^2 = R^2 + (X_C - X_L)^2$ = impedance in ohms

θ = phase angle between current and voltage

Note:

Ohm's Law gives the following:

$E_Z = I_Z Z$; $E_C = I_C X_C$; $E_R = I_R R$

And:

Power equations give us:

Total volt-amperes $= I_Z E_Z = I_Z^2 Z = I^2 Z$

Reactive volt-Amps $= I_C E_C = I_C^2 X_C = I^2 X_C$

Resistive VA (Watts) $= I_R E_R = I_R^2 R = I^2 R =$ Power In - Power Out

Therefore: $PF = \frac{P(in) - P(out)}{P(in)} = \frac{I^2 R}{I^2 Z} = \frac{R}{Z} = \cos\theta$

and DF is defined as the ratio of resistance to reactance,

$$DF = \frac{R}{X_C} = \cot\theta$$

Now we note that for "good" capacitors:

R and X_L are $<<<$ X_C such that

$Z^2 = R^2 + (X_C - X_L)^2 \cong X_C^2$ and since $Z \cong X_C$

$$PF = \frac{R}{Z} \cong \frac{R}{X_C} = DF$$

Q (figure of merit) is defined as the ratio of reactance to resistance:

$$Q = \frac{X_C}{R} = \frac{1}{DF} \cong \frac{1}{PF}$$

FIGURE 7

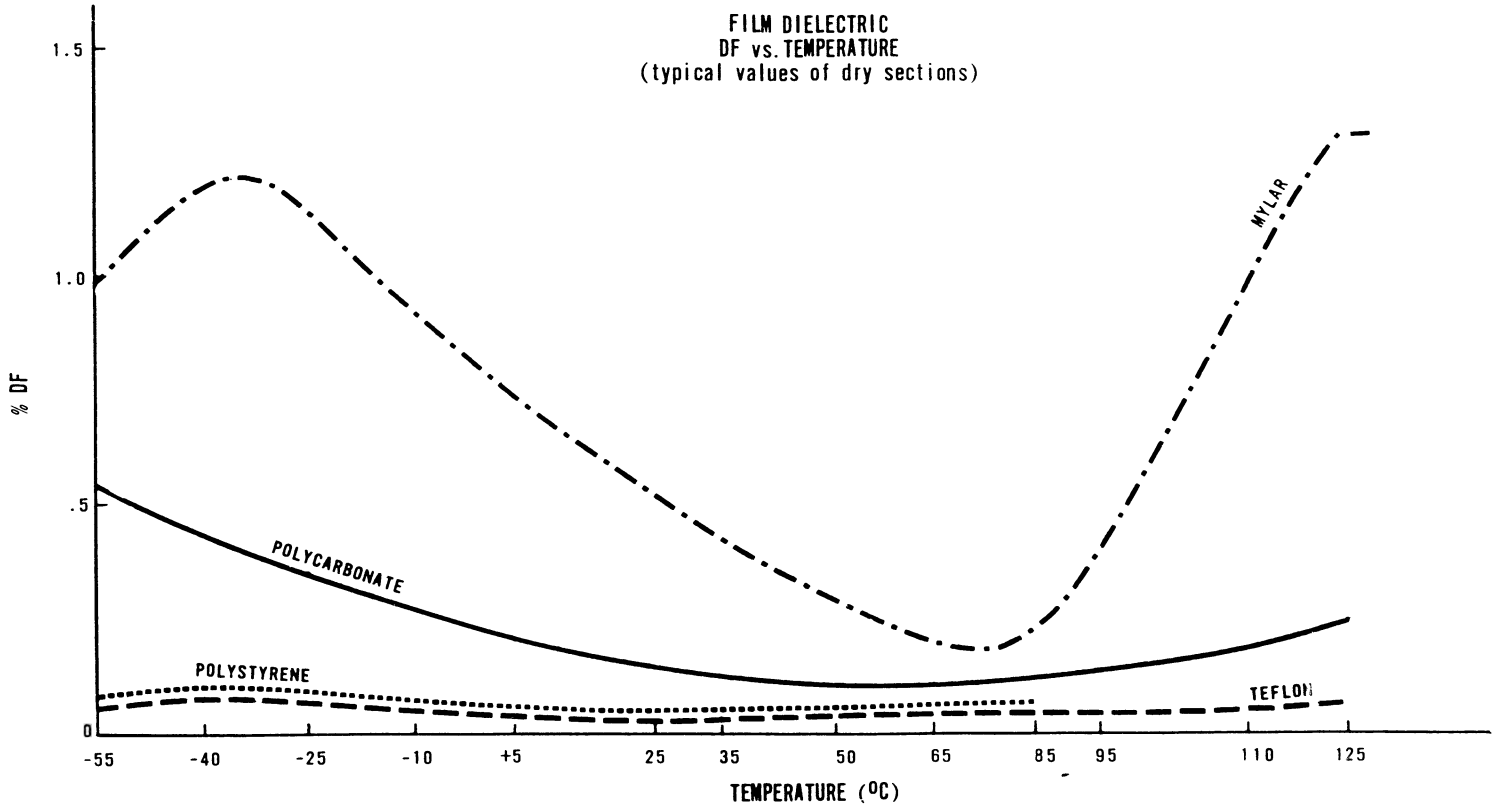

FILM DIELECTRIC
DF vs. TEMPERATURE
(typical values of dry sections)
% DF
1.5
1.0
.5
0
MYLAR
POLYCARBONATE
POLYSTYRENE
TEFLON
-55
-40
-25
-10
+5
25
35
50
65
85
95
110
125
TEMPERATURE (°C)

FIGURE 8

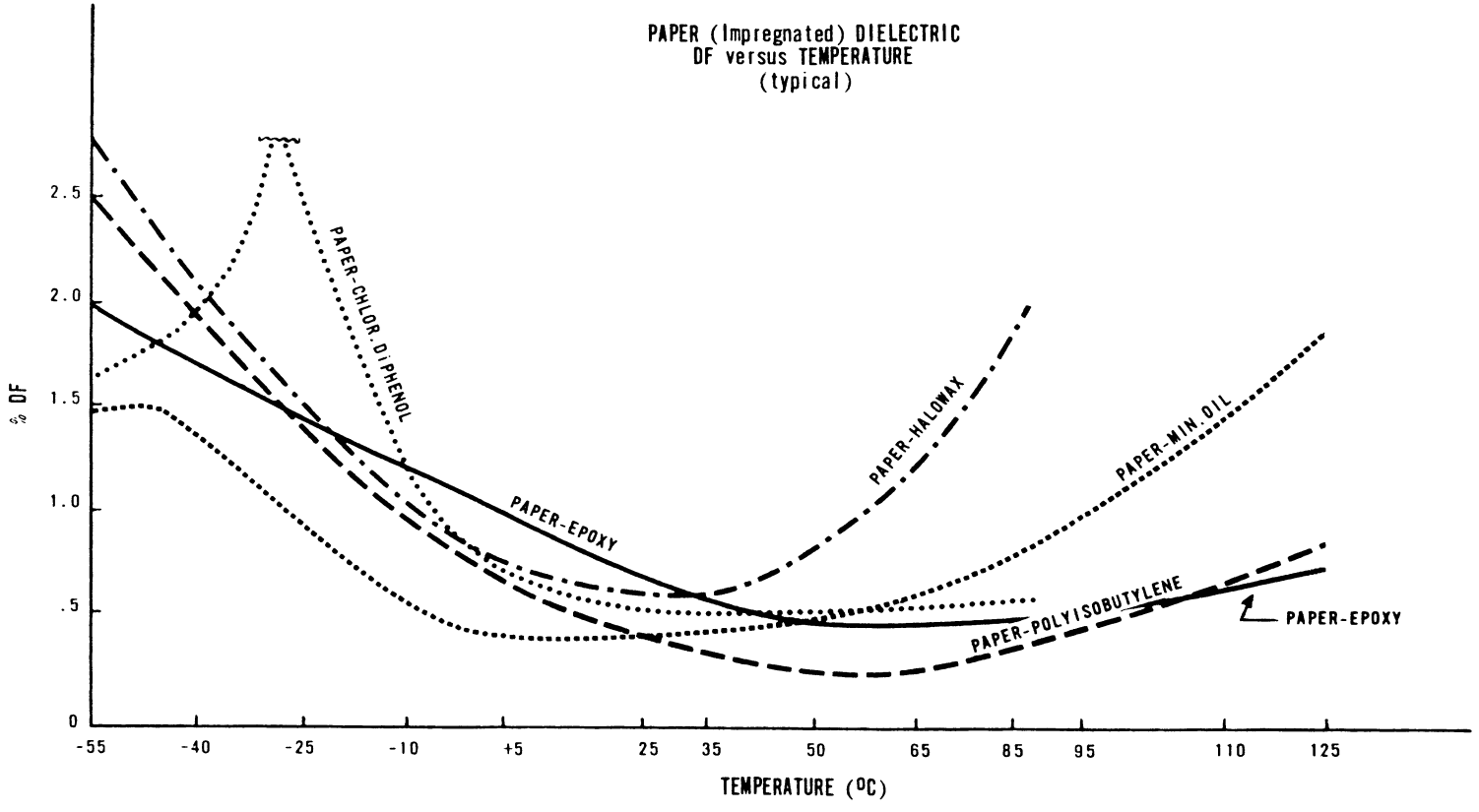

PAPER (Impregnated) DIELECTRIC
DF versus TEMPERATURE
(typical)
% DF
2.5
2.0
1.5
1.0
.5
0
-55
-40
-25
-10
+5
25
35
50
65
85
95
110
125
TEMPERATURE (°C)
PAPER-CHLOR. DIPHENOL
PAPER-EPOXY
PAPER-HALOWAX
PAPER-MIN. OIL
PAPER-POLYISOBUTYLENE
PAPER-EPOXY

FIGURE 9

12

must accept possible alterations in other characteristics in order to improve or stabilize some portion of the DF vs. Temperature curve.

No attempt will be made to present any curves of dissipation factor vs. temperature for the other dielectrics. Both the mica and glass or vitreous enamel dielectric types are very low in value and stable with temperature relative to the dissipation factor. Both types will hold a range of .03 to .1% DF over the full temperature range.

Ceramic capacitors can exhibit very steady or highly erratic DF vs. temperature curves depending upon the design, formulation material, and manufacturing processing involved. In general, room temperature values between .1% and 2.5% DF are quite common.

Electrolytic capacitors present a somewhat similar problem to that of the ceramics inasmuch as design, type of electrolyte, and processing are critical factors in the control of the power factor. Note here that the term 'dissipation factor' is rarely used in connection with electrolytics inasmuch as the approximation that PF = DF is no longer applicable. We are, in general, dealing with units that have a very high "ESR" (equivalent series resistance) compared to paper or film capacitors.

With the exception of the "solid" or dry type tantalum electrolytics which will hold a range of 3% to 6% PF fairly well over the temperature range of −55°C to +85°C, ESR values are used as a criteria for the "loss" characteristic of the aluminum and tantalum electrolytics. In this case, it is common practice to equate the "equivalent series resistance" (R) to capacitance and power factor by the following formula:

$$ESR = \frac{PF}{2\pi fC}$$

from which an equivalent PF can be extracted. Values of PF around 10% at 25°C and above are quite common. As the temperature decreases, the PF generally rises exponentially due to the rapid increase in the resistance of most electrolytes.

For the user, the DF characteristic of a capacitor is of no practical or application interest unless his circuit involves AC voltages or a fairly large AC ripple superimposed on a polarizing DC voltage. When this is the case, the extent of heat generated by the capacitor is a direct function of the "effective" DF value. This "effective" DF value is **not** the bridge DF value unless the measurement equipment and capacitor are both at rated conditions of voltage, temperature, and frequency. In critical applications, direct heat rise tests should be performed to determine this true or "effective" DF value.

For the manufacturer, however, the DF parameter is of importance as a measure of material and processes control. Since the DF value is a measure of the losses that occur within the capacitor itself — and these losses are caused by various factors including leakage current and internal lead connections — variations of DF from a normal distribution alerts the production and quality control functions to possible problems with material, processes, or operations.

Insulation Resistance Change With Temperature

An ideal dielectric would allow no electrons to flow or make its way from one electrode plate to the other through the dielectric. Unfortunately, there is no ideal dielectric obtainable — so a current of electrons does flow from one plate to the other — resulting in a "leakage current" for the capacitor. The amount

of this leakage current will depend upon many things; the type of dielectric used, the thickness of the dielectric, the magnitude of the charging voltage, the microfarad rating, the time of electrification, and the temperature. Except in the case of the "electrolytic" type capacitor, this characteristic of leakage current is expressed as "insulation resistance" which is related to leakage current by Ohm's Law ($E = IR$) where E is the impressed voltage, I is the "leakage current" and R is the "insulation resistance" (referred to as "IR").

One of the problems facing any manufacturer of capacitors is that of specifying the insulation resistance limit guarantee for his line of product. This problem arises from the fact that the insulation resistance varies directly with the capacitance rating for any given voltage and style design. In effect, if you double the capacitance, you halve the insulation resistance. Obviously, it is impossible to give a single ohmic value of insulation resistance that would be valid for all capacitance values of any given design. Fortunately, the fact that the insulation resistance and capacitance are almost exactly inversely linearly related gives a good tool for solving the problem. Thus, for any given dielectric type and design, the product of the IR (ohms) times C (farads) is almost constant. This, in turn, allows the use of the term ohm-farads, or more commonly, megohm-microfarads, to designate insulation resistance. Note that this concept is **not** megohms "per" microfarad but rather megohms "times" microfarads.

Closely aligned with the determination of insulation resistance is the limitations on equipment capability for measuring this characteristic. This equipment capability is not a problem until we are faced with measuring dielectrics that have an extremely high inherent insulation resistance such as the plastic films. Many of these type capacitors, particularly in the very low capacitance value range, are far beyond the readable scale limits of standard equipment and therefore merely register as "infinite" insulation resistance. This problem is solved by use of a "need not exceed" value. For instance, a line of capacitors may be designated as meeting an insulation resistance guarantee of "100,000 megohms times microfarads but need not exceed 500,000 megohms".

It should be noted that the time of electrification is most critical in the determination of this insulation resistance and should always be noted when specifying IR limits or values. Two minutes electrification time is quite common and in general usage although other times can be used. In general, the IR curve with time for most capacitors will follow the pattern shown in Figure 10.

Temperature has a decided effect upon the insulation resistance characteristic. Figure 10 illustrates the temperature effect on the time of electrification characteristic for any given capacitor, and Figure 11 shows a comparative analysis of the typical values for different dielectrics. What must be kept in mind when analysing Figure 11 is that these curves shown are average figures only and it is entirely possible to get individual capacitors that will vary from their average value by very large amounts, in some cases by as much as 10, or 20 to 1.

The effect of the insulation resistance value, both its magnitude and how it varies with temperature, is quite critical in circuitry where leakage of current through the capacitor can cause malfunction or undesirable effects to occur. Prime examples of this type of application are those involving DC and low AC frequencies in most blocking, coupling, and timing circuits.

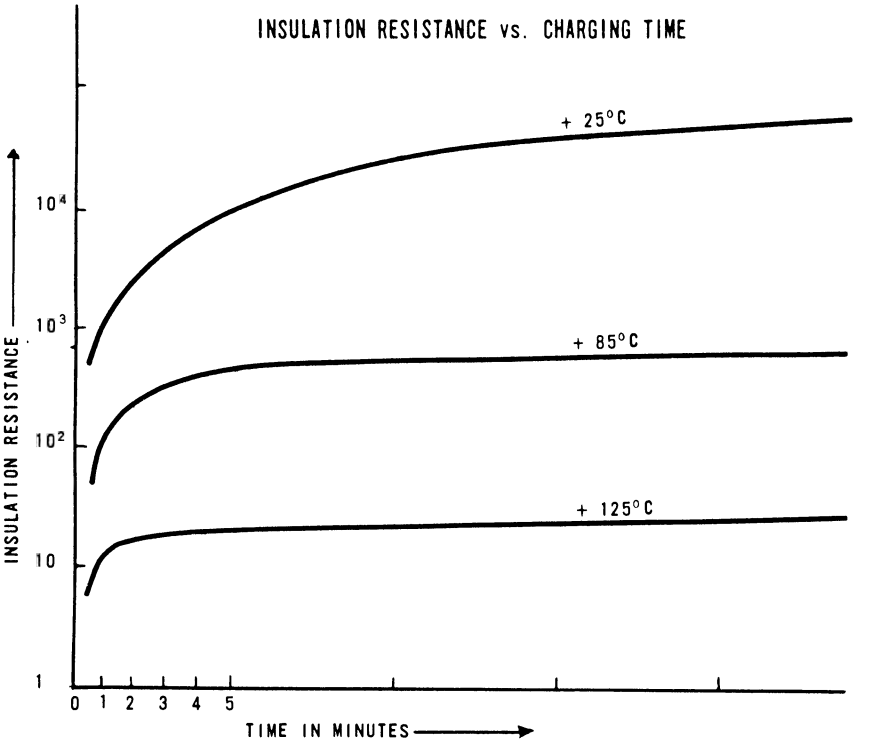


FIGURE 10

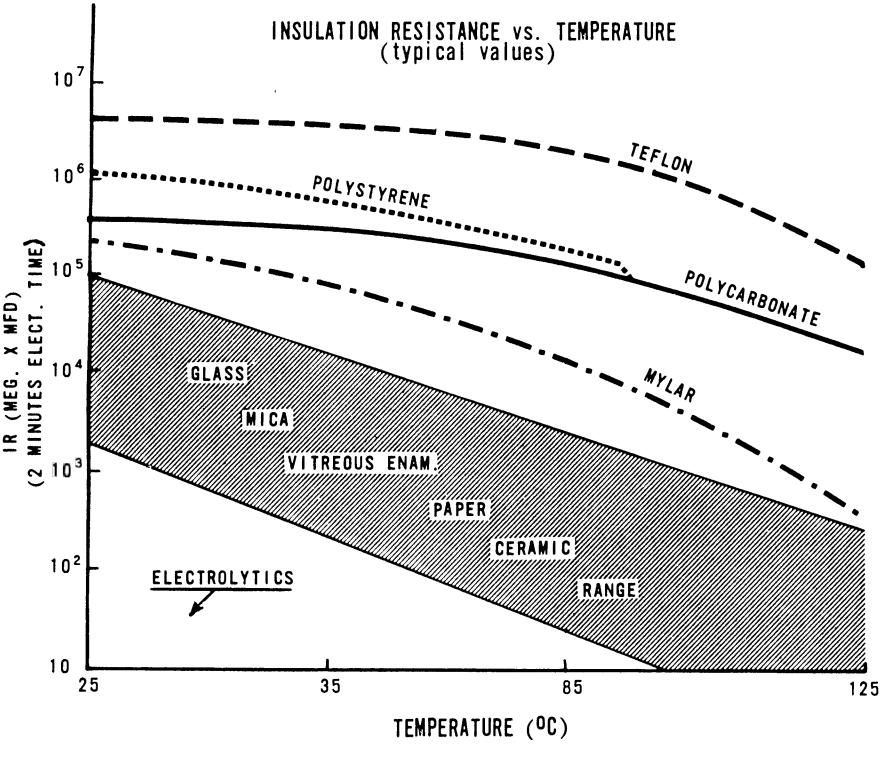
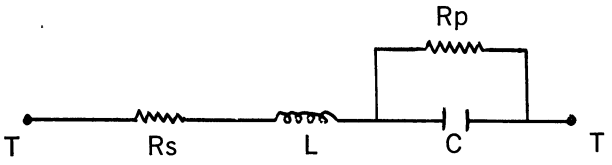


FIGURE 11

THE EFFECT OF FREQUENCY

All too often, many design engineers — though very careful in evaluating other parameters — will completely overlook frequency effects when choosing a capacitor for a particular application in a medium to high frequency circuit. Yet, upon analysis, practically all basic capacitor parameter formulas include a frequency term, most characteristics of capacitors are to some extent effected by frequency, and all capacitors have some inductance associated with their conductors and therefore must resonate (act like a pure resistor) at some frequency.

Let us first examine a simplified equivalent circuit of a capacitor wherein all distributed parameters are shown as a single "lumped" value.



Rs = Equivalent Series Resistance in Ohms
L = Inductance in Henries
C = Capacitance in Farads
Rp = Parallel (Insulation) Resistance in Ohms.

Under DC or low frequency conditions, Rs and L are negligible compared to the C and Rp combination. As the frequency increases, particularly to the mega-cycles range, both Rs and L increase. Rs increases due to a physical phenomenon called a "skin" effect where the current tends to travel only through the outer surface metal of a conductor under high frequency conditions. This appears as an increase in resistance of the conductor. L increases due to the action of the AC current flowing in the leads, electrodes, and terminals, thus generating a magnetic field around them proportional to the frequency.

Since the dielectric constant of most materials will also vary with frequency, we see that capacitance is also affected by frequency.

Further examination of the impedance equation shows that as the frequency increases, X_C tends to decrease while X_L increases in value. This, of course, means that the $(X_C\text{-}X_L)^2$ term decreases until at some frequency, the term $(X_C\text{-}X_L)^2$ will = 0 and disappear. Then Z = Rs and the capacitor will "resonate". This is the point where the capacitor appears as a pure resistor to the circuit. This "resonant" frequency for any capacitor is determined by the formula:

$$(X_C\text{-}X_L)^2 = 0 \therefore X_C = X_L \text{ or } \frac{1}{2\pi fC} = 2\pi fL$$

and: $f^2 = \frac{1}{4\pi^2 CL}$ so: f (resonance) $= \frac{1}{2\pi\sqrt{CL}}$

It also follows that if a capacitor is operated at a frequency higher than its "resonant" frequency, it will no longer be a capacitor to the circuit, but rather will appear as an inductor.

Since there are so many variables affected by frequency, no attempt to present comparative curves will be made here. As a possible guide for general areas of frequency applications for the different types of capacitors manufactured, Figure 12 can be used for an initial approximation. Specific computations and/or measurements should be used to finalize any particular application.

Figure 12 reflects a frequency range of most efficient application based on normal design values and criteria. Both upper and lower limits of frequency usage can be extended somewhat by special design and construction techniques. Low frequency losses can be reduced in some cases by special processing.

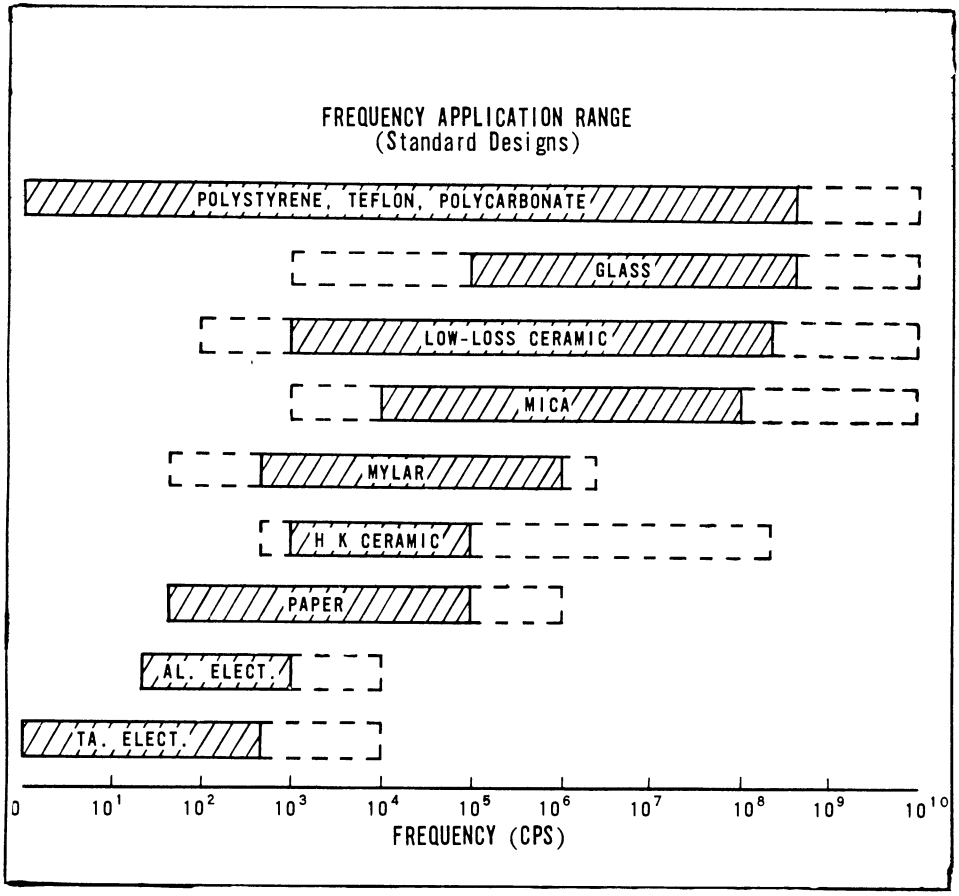


FIGURE 12

DIELECTRIC ABSORPTION

This phenomena is really a reluctance on the part of the dielectric to give up the electrons that it has stored within itself whenever the capacitor is discharged. Then, when the shorting mechanism is removed, these electrons that remained in the dielectric will, in time, accumulate on an electrode and cause a "recovery voltage" gradient to appear across the capacitor terminals. This recovery voltage, divided by the charging voltage and expressed as a percent figure, is called the "% Dielectric Absorption".

The magnitude of this % dielectric absorption figure will vary considerably for different dielectric materials and their impregnants. It is also important to note that any measured values obtained of dielectric absorption figures will be affected by the following factors:

a. Amplitude of the charging voltage
b. Charging time
c. Discharge time
d. Time after discharge that measurements are made
e. Temperature

This "reluctance" on the part of a dielectric to give up its electrons is primarily due to the polarization effect that takes place on the dielectric dipoles whenever the capacitor is energized. These electrons, in effect, become "bound" or trapped in the dielectric during the discharge period. When the shorting mechanism is removed, these "bound" electrons become "free" again and will then move to the electrode surface. This results in a potential difference between the electrodes and thus the "recovery voltage".

In addition to the "bound" electron phenomenom, a secondary factor in the magnitude of recovery voltage values is that of "free" electrons in random movement in the dielectric. These "free" electrons take finite time to move from the dielectric to the electrode, and therefore contribute to this recovery voltage — how much contribution they make is closely controlled by the "discharge" time duration

Dielectric Absorption

Conditions:	Charging Voltage	=	200 VDC
	Charging Time	=	1 minute
	Discharge Time	=	2 seconds
	Time after Discharge	=	1 minute
	Temperature	=	25°C

Dielectric	% DA
Air	0
*Polystyrene	.02
*Teflon	.02
*Polycarbonate	.08
*Mylar	.20
Mica (Ruby)	.70
Paper (Oil Impregnated)	2.0

*The addition of an oil impregnant will cause the % DA figure to become essentially that of the impregnant. (Approximately 2.0 for most oils.)

FIGURE 13

Figure 13 shows approximate comparative values of the % dielectric absorption figure for some typical dielectrics. These, you will note, are at the given set of conditions. A change in any of the conditions will cause a variation in the dielectric absorption figure.

Dielectric absorption becomes a critical factor in circuiting that is highly dependent upon the "speed of response" or time delays in the charge and discharge cycles of a pulse circuit such as those found in welding, radar, telemetering, servo-mechanisms, computer, etc., applications.

THE METALLIZED DIELECTRIC

Much confusion exists in the minds of many design engineers relative to the subject of metallized dielectrics. This is extremely unfortunate because this confusion has resulted in the exclusion of a most valuable tool from many circuit designs. There should not be, and there is nothing any more mysterious about the application of a metallized dielectric capacitor than there is about the application of a non-metallized dielectric unit. The key word here is "application" and by this we mean **proper** application which certainly applies in either case. A close examination of the basic aspects of the metallized dielectric should help to clear up this unnecessary confusion.

Physical Construction

The construction of a metallized dielectric capacitor is quite similar to that of a non-metallized unit except for the electrodes and end terminations. Unlike the non-metallized dielectric design that winds separate sheets of dielectric and metal foil, the metal electrodes of the metallized dielectric design are sprayed or evaporated directly onto the dielectric sheets prior to winding. This results in a much thinner electrode and a reduction in the air film portion of the total dielectric for the metallized unit.

The end terminations of the metallized unit are accomplished by applying a finely divided molten metal spray to the capacitor roll ends, to which the leads are then soldered. For the non-metallized dielectric units, two types of end connections are used:

a. Inserted tab construction consists of metal strip terminals which are inserted between the windings of the capacitor roll and contact the appropriate electrodes.

b. For an extended foil construction type unit, the electrodes are extended beyond the dielectric material during winding. One of the electrodes extends out of one end of the capacitor roll and the other electrode extends out the opposite roll end. These two ends are then pressed to form a smooth surface and terminals added by soldering or welding.

Volumetric Efficiency

From the foregoing, the volumetric advantage of the metallized design is self-evident from the physical reduction of electrode material and air film. This advantage is more evident and becomes more pronounced as the capacitance rating increases. At the smaller capacitance ratings (under approximately .1 Mfd), very little advantage is evident since the end terminations, casings, and end seals, form a disproportionate part of the total volume and are approximately equal for both types of units.

Self-Healing Property

This unique feature of the metallized design is a direct result of the extreme thinness of the electrode metal material, and offers a distinct advantage over the non-metallized type of capacitor.

Whenever a flaw or weak spot in the dielectric results in a direct short condition, the stored electrons in the capacitor and the associated circuitry (when available) will immediately "avalanche" to cross at that point. This density concentration results in a very high current condition which in turn provides sufficient energy in the form of heat to vaporize the extremely thin metallic electrode in the immediate vicinity of the shorted spot. As a result of this vaporization process, the short condition is removed and the capacitor is again operational. This is known as the "clearing" or "self-healing" process.

An average "self-clearing" operation requires only micro-watts of power and is usually accomplished in micro-seconds.

Proper Application

The proper application of a metallized dielectric capacitor is a matter of understanding what happens during a "self-healing" process and what factors control this process.

Based on today's commercially available metallized electrodes (aluminum and zinc) materials, the energy required for a normal clearing is approximately 10 micro watt-seconds. This means that if energy is available only from the capacitor itself, there is a relationship between the capacitance rating and charging voltage below which clearings may be questionable. Figure 14 shows this relationship.

The figures derived in Figure 14 should not be used as a hard and fast rule, since they are approximations based on an average case of a "normal" clearing. Variations from the "normal" case can be quite wide depending on the extent of the short condition, current limiting features of associated circuitry, and the amount and availability of stored energy external to the capacitor.

During the self-healing process, the circuit will experience a transient voltage drop. The magnitude of this voltage drop will depend on the capacitance, energy required to clear, and the voltage level to which the capacitor is charged.

Figure 15 shows the derivation of the formula relating the capacitance, charging voltage, energy required to clear, and the voltage drop that will occur on the capacitor during the clearing operation.

Capacitance — Voltage Limits

$W = \frac{1}{2} CE^2$ W = Energy (Micro-Watt-Seconds) ∴ For 10 Micro-Watt-Seconds,

C = Capacitance (Micro-farads)

E = Voltage (Volts)

$$E^2 = \frac{2 \times 10}{C} \quad \therefore E = \frac{4.5}{\sqrt{C}}$$

Capacitance (uf)	Charging Voltage (Volts)
10.0	1.4
1.0	4.5
.1	14.2
.01	45.0
.001	142.0

FIGURE 14

Capacitor Voltage Drop During Clearing

Given: C = Capacitance

E_B = Voltage on capacitor before clearing

E_A = Voltage on capacitor after clearing

E_D = Voltage drop on capacitor during clearing

W_C = Energy required to clear

$\frac{1}{2}CE_B^2$ = Energy of capacitor prior to clearing

$\frac{1}{2}CE_A^2$ = Energy of capacitor immediately following clearing

$E_D = E_B - E_A$; $E_A = E_B - E_D$

$$W_C = \tfrac{1}{2}CE_B^2 - \tfrac{1}{2}CE_A^2 = \tfrac{1}{2}C(E_B^2 - E_A^2) = \tfrac{1}{2}C(E_B - E_A)(E_B + E_A)$$

Now, since $E_B - E_A = E_D$; and $E_A = E_B - E_D$ we get:

$$W_C = \tfrac{1}{2}CE_D(E_B + E_B - E_D) = \tfrac{1}{2}CE_D(2E_B - E_D) = C(E_BE_D - \frac{E_D^2}{2}) \quad \text{Eq. (1)}$$

We note equation (1) is in the form of a quadratic in E_D; so, by rearranging and transposing:

$\frac{1}{2}CE_D^2 - CE_BE_D + W_C = 0$ and applying the quadratic formula:

$$E_D = \frac{CE_B \pm \sqrt{C^2E_B^2 - 2CW_C}}{C} = E_B \pm \sqrt{E_B^2 - \frac{2W_C}{C}}$$

$$\therefore E_D = E_B - \sqrt{E_B^2 - \frac{2W_C}{C}} \quad \text{Since the positive root is not applicable. Eq. (2)}$$

As an approximation we note Eq. (1):

$W_C = C(E_BE_D - \frac{E_D^2}{2})$; and since E_D is extremely small in the general case compared to E_B, we discard the $\frac{E_D^2}{2}$ term, thus:

$$W_C = CE_BE_D \text{ or } E_D = \frac{W_C}{E_BC}$$

Figure 15

For an example of the application of both formulas (2) and (3) from Figure 15:

E_B = 100 VDC (Charging Voltage)

C = 1.0 MFD

W_C = 10 Micro-Watt-Seconds (Energy required to clear)

By Equation (2):

$$E_D = E_B - \sqrt{E_B^2 - \frac{2W_C}{C}} = 100 - \sqrt{10{,}000 - 20} = 100 - 99.9 = \textbf{.1 volt}$$

By Equation (3) Approximation):

$$E_D = \frac{W_C}{E_B C} = \frac{10}{100 \times 1} = \textbf{.1 volt}$$

For the case where W_C = 100 Microwatt-Seconds:

$$E_D = 100 - \sqrt{10{,}000 - 200} = 100 - 99.0 = \textbf{1.0 volt}$$

$$E_D = \frac{W_C}{E_B C} = \frac{100}{100 \times 1} = \textbf{1.0 volt}$$

It is apparent from the foregoing that proper thought and consideration must be exercised prior to the application of a metallized dielectric in any circuit that may be abnormally sensitive to small voltage transients of very short duration. A classic example would be a computer that depends on a very small voltage change signal as its means of storing information in its memory banks.

When and if these clearing or self-healing functions take place, the capacitor becomes a broadband noise generator due to the arc discharge nature of the clearing. This could be critical in circuitry that requires an extremely low noise level limit for correct functioning.

Test Voltage Limitations

A fundamental difference between a metallized and a non-metallized dielectric must be recognized when dielectric withstanding voltage tests are applied. It is not uncommon to apply overvoltage tests of 200%, 250%, and 300% of rated voltage for short periods of time to a non-metallized dielectric. This practice must be carefully avoided when testing metallized units. In a non-metallized design, the air and/or impregnant film layer that is in series with the dielectric material is a much larger % of the total dielectric thickness than in a metallized unit. Consequently, when an equivalent voltage is applied to the two designs, the resultant voltage stress on the dielectric material in the metallized design is actually higher than for the equivalent non-metallized unit. Thus, the application of 250% rated voltage might have no apparent effect on the non-metallized design, but could result in exceeding the "sparking" breakdown level of the metallized design.

As a clarification example, we take a newly manufactured unit and apply 125% rated voltage for one minute and obtain a few clearings. Now we raise the voltage to 150% of rated and obtain a few more clearings. We continue this process until we reach a point where the clearings become continuous and eventually permanent breakdown occurs. In this case, the sparking voltage level of the capacitor has been exceeded.

While it is true that exact levels may vary slightly for the different dielectrics, the general rules followed for metallized dielectrics are as follows:

A. The maximum overvoltage limit for long-time applications that self-healings can occur without detriment to the capacitor is 140% rated volts (common life test voltage).
B. The maximum overvoltage limit for short-time (one minute or less) applications is 150% to 200% rated volts depending on the dielectric material.

Clearing Occurances During Service Life

Once a metallized dielectric capacitor has been carefully manufactured, tested, and properly applied in a circuit, it is a fairly rare occurence to have further clearings during normal service life. In many applications, particularly when applied at less than 100% of rated voltage and at less than maximum ambient temperature conditions, the unit will probably function for years without a clearing. What should be recognized here is the fact that in order for a self-healing action to occur, stresses must be present that will induce the shorted condition, and voltage and temperature derating both tend to minimize this short producing condition.

ENVIRONMENTAL EFFECTS ON CAPACITORS

The characteristic behavior and service life of all capacitors are highly dependent upon the environments to which they are exposed. The following section is a capsule summary of the individual environmental factors that are most critical in their effect on capacitors. The component and/or design engineer should recognize and consider not only the implications of each individual environmental factor on his application, but also must evaluate the effect that results from various combinations of these factors.

Many perfectly good capacitors are misapplied and will fail when they are designed into equipment that subsequently must see environmental conditions that exceed, or were not considered, in the design capabilities of the capacitor.

Ambient Temperature

The temperature (ambient) of the immediate space surrounding the capacitor is of critical importance since this is one of the determining factors on the temperature at which the dielectric operates.

A. **Service Life.** Service life of a capacitor will decrease with an increase in temperature. One of the factors affecting wear-out of a capacitor is dielectric degradation resulting from chemical activity with time.
B. **Capacitance.** Capacitance will vary up or down with temperature depending on the dielectric and construction. The temperature can cause two distinct actions to take place that will effect capacitance. Both the dielectric constant of the material and the spacing between the electrodes can be altered. Again, depending on the materials, these two actions will tend to either reinforce or offset each other.
C. **Insulation Resistance.** The insulation resistance decreases with an

increase in temperature due to the increased electron activity (velocity) caused by the temperature increase. A change in the resistive abilities of the dielectric will also result from a temperature variation.

D. **Dissipation Factor.** The dissipation factor is a very complex function of temperature and may vary either up or down with increased temperature depending on the dielectric material. In some cases, several variations will take place on the same style of capacitor over its listed usable temperature range.

E. **Dielectric Strength.** The dielectric strength (breakdown voltage stress level) decreases with an increase in temperature. As temperature increases, the chemical activity increases, which in turn will cause a change in physical and/or electrical properties of the dielectric.

F. **Sealing.** For the case of hermetically sealed capacitors, an increase in temperature results in an increase in internal pressure. If this pressure becomes great enough, it will eventually rupture the hermetic seal with possible resultant impregnant leakage and moisture susceptibility.

Humidity (Moisture)

The effect of moisture on a capacitor can be very apparent from parametric changes, reduced service life, and in some cases, early failures from gross moisture penetration of the unit. Although moisture will cause variations and atypical behavior in the capacitance, dissipation factor, and dielectric breakdown strength parameters of a capacitor, the most noticeable parameter effect is that of the decrease in the insulation resistance characteristic.

Corrosion of a metal-cased unit, under excessive moisture conditions, can lead to mechanical failure unless proper coating (plating) procedures are observed relative to the lead wires, terminals and/or metal case itself. These mechanical failures may also result in later electrical characteristics malfunctions.

Of considerable interest to a component or design engineer faced with miniaturization requirements is the abilities of the various non-hermetically sealed styles of capacitors to withstand moisture environments. Generally, the non-hermetic unit is considerably smaller than an equivalent hermetically sealed unit.

First, let us investigate the normal purpose of the familiar moisture type tests that are generally referred to or called out by most military capacitor specifications. These specifications will invariably refer to MIL-STD-202 which details how these tests are to be performed.

A. **Immersion Cycling.** This is a test where the capacitors are immersed for two or more cycles in either fresh or salt water for a period of from 15 to 60 minutes per cycle.

B. **Humidity Exposure.** In this test the capacitors are subjected to exposure to 90 to 95% relative humidity at 40°C for a period of 96 or more hours.

C. **Moisture Resistance.** Here, a combination of temperature cycling and humidity exposure is used on a cycling basis for 10 cycles, each cycle lasting 24 hours. Sub-zero temperature exposure and vibration are also included in the cycling phase.

All three of the above tests were originally designed to test the **effectiveness** of an **hermetic seal,** and represent extremely accelerated conditions compared to almost all field conditions. As a test for an hermetic seal, they are very effective and perform their function very well.

In any **non-hermetic** designed unit such as the plastic case or plastic wrap-epoxy end-filled style of capacitor, moisture vapor can and will penetrate through the epoxy and/or plastic casings. How much vapor penetrates will depend on the time involved, the efficiency of the bonding juncture between the epoxy and the lead, density of the plastic material, and the thickness of the epoxy and/or plastic material used.

From the foregoing, it is obvious that units can be designed deliberately to pass the MIL-STD-202 accelerated tests by making the unit much larger than normal by increasing thicknesses of epoxy, etc. This, however, means that the sizes now approach those of equivalent metal-cased, hermetically sealed units, thus defeating the original purpose of obtaining a smaller unit.

The standard, small, commercial designs of non-hermetically sealed units are not usually designed to pass the MIL-STD-202 accelerated moisture type tests. The fact that some of the units will pass these tests should not be misinterpreted to mean that all units should or will pass the tests on a **consistent** lot-by-lot basis.

A strong distinction should be made here between paper and film dielectric designs. Non-hermetic designs of capacitors that use paper as all or part of their dielectric are much more vulnerable to moisture than those designs using film as a dielectric. The reason here is that once the moisture vapor has penetrated to the dielectric, the paper will absorb this moisture, thus trapping it and eventually destroying the insulation resistance properties of the paper. In the case of the film dielectric, there is practically no absorption of the vapor by the film and it will either be cycled back out of the capacitor or remain in the air space next to the film surface. While the vapor is in the capacitor, it causes a degradation in the insulation resistance properties of the capacitor. Usually, however, the resultant insulation resistance value of the film dielectric capacitor with moisture vapor present, is still superior to the paper dielectric capacitor with absorbed moisture.

The obvious point here is that in many cases, a completely suitable non-hermetic style unit is discarded for possible usage in a circuit only because it will not pass an arbitrary accelerated moisture condition that has no relation to actual field conditions.

Vibration, Shock, Acceleration

A capacitor can be mechanically destroyed or damaged or may malfunction if it is not designed and manufactured to withstand whatever vibration, shock, or acceleration conditions are present in the application. Movement of the internal assembly inside the container can cause capacitance changes, dielectric or insulation failures due to physical movement of the electrode foils or internal roll connections, and fatigue failures of the terminal connections. In addition, external terminals, the case, and mounting brackets, are subject to mechanical stress distortions.

Barometric Pressure

The altitude at which hermetically sealed capacitors are to be operated will control the voltage rating of the capacitor terminals. As barometric pressure decreases, the ability of the terminal to withstand voltage arc-over also decreases.

For liquid-impregnated capacitors, the differential between the internal and external pressure becomes greater when the external pressure is reduced. This puts added stresses on the seams and terminal seals and can result in subsequent rupture of the hermetic seal and consequent impregnant leakage.

Capacitance can be affected by internal dimensional changes due to pressure differentials, and internal arc-overs can result when a partial vacuum condition exists in the capacitor.

Heat transfer by convection is decreased as the altitude is increased. This condition must be evaluated in the cases where the application results in heat generation within the capacitor.

Radiation

With the advent of space exploration, radiation capabilities of capacitors has become an environmental criteria that must be considered. Not surprisingly, this factor has the least data available upon which evaluations and decisions can be made.

Early studies with dielectric materials were more concerned with the physical changes that took place under radiation than with the changes in electrical properties. This led to the necessity of making an assumption that there would be a direct correlation between physical and electrical changes. Extensive studies are now under way to evaluate the degree of validity in this assumption.

Figure 16 is an approximate summation of the radiation resistance properties of various dielectric materials used in making capacitors. It is based on the **physical** changes taking place and should be used as a guide only. Later data based on **electrical** degredation levels may or may not support the conclusions shown.

It should also be pointed out that special techniques in manufacturing and processing can be applied to improve some of the dielectrics shown.

Dielectric Radiation Resistance Chart

Material	Absorbed Energy Level for Approx. 25% Degredation
Ceramics	Highly Resistant (no levels given)
Glass	Highly Resistant (no levels given)
Mica	Highly Resistant (no levels given)
Polystyrene	Over 1×10^{11} ergs/gram
Polycarbonate	Approx. 2×10^{10} ergs/gram
Mylar	Approx. 1×10^{10} ergs/gram
Polyethylene	9.3×10^{9} ergs/gram
Cellulose Acetate	1.9×10^{9} ergs/gram
Teflon	1×10^{7} ergs/gram
Electrolytic*	Very susceptible (no values given)
Oil filled Capacitors	Very susceptible (no values given)

*Not including Solid slug Tantalum

FIGURE 16

RELIABILITY

In any discussion of reliability, it is most necessary that all persons concerned talk from a common basis of understanding relative to concepts, definitions, and procedures. As related to capacitors, it is important to keep in mind that our basis of understanding for what follows is keyed to the "component part" rather than the "system" concept of reliability.

Need for Reliability

Not too many years ago, the failure of an individual component in an equipment was largely a matter of frustrating annoyance while it was located and replaced at small or moderate cost. Not so anymore — as the complexity of designs and applications multiplied at a rapid pace, the cost of a failure by an individual component in time, money, and annoyance increased on an exponential curve. Even now, in this beginning age of missiles and space vehicles, a single component failure can literally cost a fortune, delay progress many months, and possibly result in the loss of human lives.

The inevitable result of this frightening glimpse of potential dangers that exist today, and will become increasingly acute in the future, is a desperate need for components that just won't ever fail! Of course, those "magic" components do not exist, so we must then strive to obtain components that will operate without failure for a certain known period of time. In other words, we want units that will have a certain "reliability."

Reliability Defined

Reliability can be defined in many different ways, depending on the person who defines it, the circumstances to which it is applied, and the criteria that are used as measurement standards in evaluating it. However, the classical general definition that "Reliability is the probability that a device will perform satisfactorily for a specified operating period under specified operating conditions" will most certainly apply to all specialized definitions.

Measure of Reliability

The fact that a certain component will "perform satisfactorily" in one application and then fail when used in a second (say more stringent) application, doesn't necessarily mean that the component suddenly changed from being "reliable" to "unreliable." Obviously, the component may be reliable enough for the first application, but **not reliable enough** for the second one. In other words, its "level of reliability" was not high enough for the second application.

We now see that we must have some means of indicating just how reliable a component is, or what its "level of reliability" is. This is accomplished by the use of the terms "Failure Rate (% per 1000 hrs.)" and/or "Mean Time Between Failures (MTBF)."

Further, we must be very careful to qualify and make clear the limiting conditions that govern the usage of these reliability terms. For the purposes of this presentation, all references to "Failure Rate" and "Mean Time Between Failures" are applicable only to that time span in the life of a device beginning after the removal of the "early failures" and prior to the beginning of "wear-out." This time span is commonly referred to as the "useful life" period of the device. (Fig. 17.)

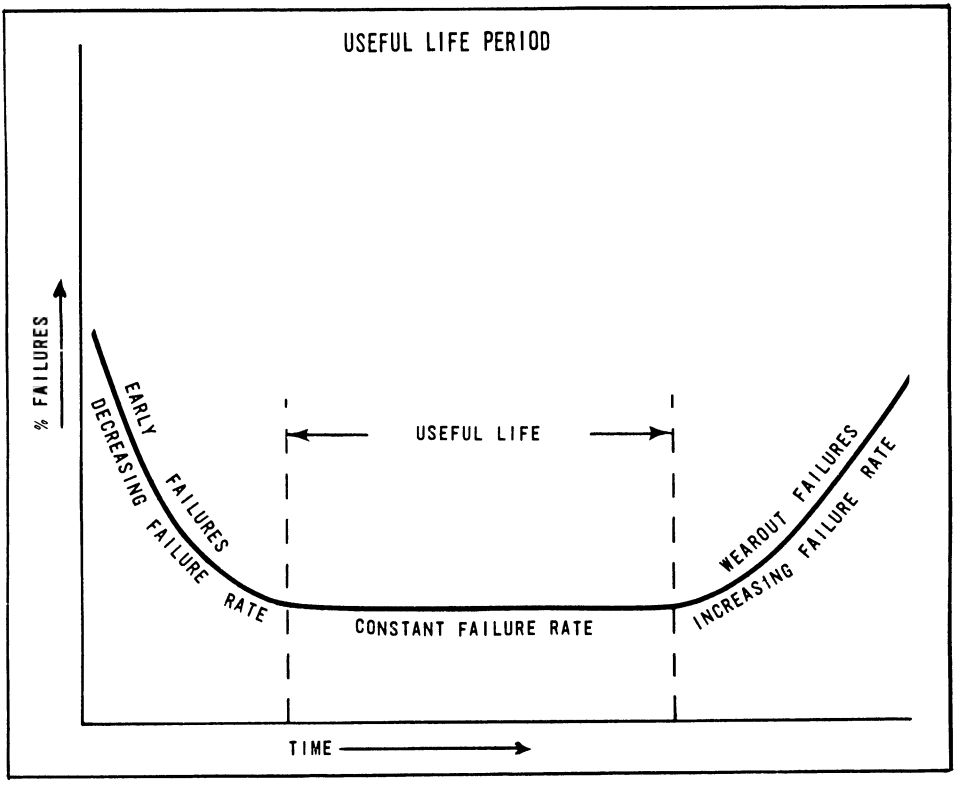


FIGURE 17

(a) Failure Rate

In its simplest context, once the definition of what constitutes a "failure" (or malfunction) has been precisely determined, failure rate is a measure of how often or with what frequency a device will fail to give "satisfactory performance." Further, this frequency of unsatisfactory performance must be and is correlated to a certain time period span, resulting in the failure rate being measured in "number of failures per unit of operating time."

For the case of a "repairable" equipment, the above definition is quite clear-cut and presents no particular difficulties. As each failure occurs, the equipment is repaired and put back into service.

In the case of a "non-repairable" equipment or device, the term "number of failures per unit of time" has no real meaning beyond the first failure. Therefore, a slight variation in the method of denoting failure rate becomes necessary. If we now take a group of these "non-repairable" devices and test them over a certain period of time, a certain percentage will fail within this time period. Now we can state the failure rate as a "percent failures per unit time period."

What is really being said when the "percent failures per unit time" figure is used for "non-repairable" devices is two things: (Assume a FR of 1% per 1000 hours).

(1) For one single device, there is a 1% probability that it will fail within the first 1000 hours of operation.

(2) For a group of identical devices, 1% of the total units will probably fail within the first 1000 hours of operation.

(b) Mean Time Between Failures (MTBF)*

The "mean time between failures" figure for an equipment is by definition the reciprocal of the failure rate. Just as the failure rate gives you the number or percent of failures per unit time, the MTBF gives you the unit time per failure.

A note of caution that must be observed here is the relationship between this MTBF and the useful life figure for a device. For clearer understanding, we must realize that the device will exhibit this MTBF reliability characteristic **only during the useful life** of the device. This does **not** necessarily mean that the device can be operated for the total time shown by the MTBF. An example will help clarify this point.

Assume a device that has a "useful life" of 100,000 hours, and exhibits a failure rate during this useful life of .01% per 1000 hrs. By definition, the MTBF of the device is 10,000,000 hours. What the user must realize here is that during the 100,000 hours of useful life of the device, it will exhibit a characteristic of 10 million hours between failures, but at the end of 100,000 hours of usage, the device should be replaced since it has reached its beginning of "wear-out" condition.

One might ask then, "What good is this MTBF figure? It seems to be an artificial figure with no meaning!" On the contrary, it is extremely meaningful in that it tells us **how reliable** the device is **during its useful life.**

Failure Rate Conditions

A FR figure by itself is totally useless. It must be qualified by a confidence level and operating conditions. And what does this term "confidence level" mean? Simply stated, it is a measure of how sure you are of the FR figure which was obtained by testing some units under certain operating conditions.

Confidence level then is really a meature of the statistical accuracy you attach to the answers you get from your tests. And this statistical accuracy will depend on the amount of testing done. The greater the amount of testing, the higher the confidence level for any particular FR derived from those tests.

All well and good — but what am I really saying when I say, for instance, that my confidence level is 60% for a FR of .08%/1000 hours?

Well — I am saying that due to the statistics associated with my testing program, the probability that .08%/1000 hours is the correct or true FR is 60%. There is a 40% probability that the correct or true FR is different than .08%/1000 hours. Note — I didn't say "better" or "worse" than .08%/1000 hours, I said "different" — It could be either!

Finally, the operating conditions applying to the failure rate figure must be stated. In all cases, a failure rate figure is established at certain test conditions and really applies **only** at those conditions. However, most test conditions are highly accelerated over "use" conditions of voltage and temperature. This leads to the problem of translating a failure rate figure obtained at one set of temperature and voltage conditions to an equivalent failure rate figure at some other temperature and voltage condition. This is accomplished by use of "acceleration" factors.

For the case where non-repairable equipment is involved, the term "Mean Time To Failure (MTTF) is commonly used since only the time to the first failure is of interest. For the purposes of this discussion, these terms can be used interchangeably.

Voltage Acceleration Factor

In essence, if a capacitor is operated for a certain time period at some voltage stress level 1, the voltage acceleration factor is a means by which this time of operation at voltage (E_1) is equated to an equivalent time at some other voltage (E_2). The formula for this "Voltage Power Law" is shown in Figure 18.

Voltage Power Law
(Constant Temperature)

$$\frac{L_1}{L_2} = \left(\frac{E_2}{E_1}\right)^n$$

where E_1 = Voltage at Condition 1; L_1 = Life at E_1
where E_2 = Voltage at Condition 2; L_2 = Life at E_2
where n = Proper exponent for the dielectric material and voltage stress area under consideration.

FIGURE 18

The expression $\left(\frac{E_2}{E_1}\right)^n$ is the acceleration factor and as can be seen is dependent upon the proper value of the exponent n. This value of n will vary for different dielectric materials. It is also controlled by design, processing, and test conditions. However, with all other considerations being equal, life and/or reliability will follow this voltage power law quite closely.

The real problem is in determining what the proper value of n is for specific dielectrics over specific voltage stress levels.

For clarification, we'll use the following example with the following assumptions:

(1) Assume an exponent n = 5 for paper-oil capacitors over the voltage stress level between 140% and 100% of rated volage.
(2) United were tested and lasted 10,000 hours at 140% rated voltage before failure occurred.
(3) Temperature was constant at 85° during the test.

Question: How long would the units have lasted at 100% rated volts and 85°C before failure?

$$L_{100} = L_{140}\left(\frac{E_{140}}{E_{100}}\right)^5 = 10{,}000\left(\frac{1.4}{1.0}\right)^5 = 10{,}000\ (5.36) = 53{,}600 \text{ hours.}$$

The "acceleration" factor for this example is 5.36 and would be valid only for **this dielectric** over **this voltage stress area.**

An important point to remember here is that the acceleration factor for any specific dielectric material will **not** be constant over the entire voltage stress design limits. It will **vary** with the voltage stress limits.

A final example will illustrate this point of a variable exponent with voltage stress ranges.

Assume: n = 5 for the area 140% RV to 100% RV
n = 3 for the area 100% RV to 50% RV
n = 2 for the area 50% RV to 25% RV
Temperature is constant.

If a blind assumption were made that the 5th power law applied over the entire voltage stress range, then the acceleration factor to move from 140% RV to 25% RV would be:

$$\left(\frac{1.4}{.25}\right)^5 = (5.6)^5 = 5{,}507.$$

While in reality, the proper acceleration factor should be:

$$\left(\frac{1.4}{1.0}\right)^5 \left(\frac{1.0}{.5}\right)^3 \left(\frac{.5}{.25}\right)^2 = (1.4)^5\,(2)^3\,(2)^2 = 5.36\,(8)\,(4) = 171.5$$

Temperature Acceleration Factor

The derivation of the temperature acceleration factor is somewhat similar in concept to the voltage factor. It is based on a chemical activity rule that says, "For every 10°C increase in temperature, life will be cut in half."

This statement, if followed literally, would mean that the capacitor would realize the same benefit of doubling its life expectancy for a 10°C reduction in temperature whether from 125°C to 115°C or 35° to 25°C. Again, we are faced with a variable exponent depending on the stress area concerned.

Temperature Rule

(Contant Voltage)

$$\frac{L_1}{L_2} = 2^{\left(\frac{T_2 - T_1}{n}\right)}$$

where T_1 = Temp. at Condition 1; L_1 = life at T_1
where T_2 = Temp. at Condition 2; L_2 = life at T_2
where n = °C rule applicable for the temperature stress area under consideration.

FIGURE 19

Here, the expression $2^{\left(\frac{T_2 - T_1}{n}\right)}$ is the acceleration factor for the temperature with n varying for the dielectric and the temperature stress areas concerned.

Example:

(1) Assume n = 10°C for temperature stress area concerned.
(2) 10,000 hours testing at 125°C before failure.

Question: How long would the units have lasted at 85°C before failure?

$$L_1 = L_2\, 2^{\left(\frac{T_2 - T_1}{n}\right)} = (10{,}000)\, 2^4 = 160{,}000 \text{ hours.}$$

For this example the acceleration factor would be 16.

Calculation of Failure Rate

Since the failure rate is an expression of the "probability" of failure, it is quite obvious that the determination of a failure rate figure must be based upon the proper "probability function" that fits the testing and failure mode criteria of the component involved.

For capacitors, the basic mathematical model used in determining failure rate utilizes a probability density function known as the "Weibull" distribution. However, a further simplification from the highly complex general Weibull method is made possible by the fact that during their "useful life" period, most capacitors will follow a constant failure rate pattern very closely. Thus, by assuming that the failure rate **is** constant, an "exponential distribution" characteristic (which is a special case of Weibull) can be used. This simplifies the mathematics and allows the use of the "Chi-Square" formula to calculate the failure rate. Figure 20 shows the analysis of the Chi-Square formula.

Chi-Square Formula Analysis

Basic Assumption: Constant failure rate mode applies.

Basic Equation : $\theta = \frac{2r\hat{\theta}}{\chi^2}$ where θ = mean-time-to-failure (MTTF)
$\hat{\theta}$ = best estimate of MTTF
r = number of failures
χ^2 = chi-square value

The chi-square (χ^2) value is obtained from statistical tables and is a function of the confidence level and degrees of freedom. The degrees of freedom value is, in turn, a function of the number of failures (r).

Now : $\lambda = \frac{1}{\theta}$ where λ = failure rate per unit of time

Therefore : $\lambda = \frac{\chi^2}{2r\hat{\theta}}$

Additionally : $\hat{\theta} = \frac{T}{r}$ where T = total times of all units on test (no. of units) $\times$ (time on test)

Therefore : $r\hat{\theta} = T$

And : $\lambda = \frac{\chi^2}{2T}$; which is the useable equation.

Converting to % per 1000 hours gives us our working equation:

$$\frac{\%\,\lambda}{1000 \text{ hours}} = \frac{\chi^2 \times 10^5}{2T}$$

FIGURE 20

SUMMARY

In this paper we have endeavored to acquaint the component and design engineer with an awareness of the multitude of factors that should be considered when an application for capacitors must be evaluated in his circuit. It is also true that in many cases the circuit requirements will automatically exclude the use of certain types, or reduce the number of dielectric types that can fulfill the required function to several choices. At this point, size and economics can also become critical factors in "proper" selection.

With the possible exception of a few very critical circuit applications, more than one type of capacitor **can** be used in most applications. Even so, there is still one **optimum** type and it is the responsibility of **both** the circuit engineers and the manufacturers to determine this optimum unit.

Generally, it is not a question of "shall I or shall I not" use a capacitor — it is "which" capacitor shall I use?

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